MULTIPLE ANTHROPOGENIC TRACER DISTRIBUTIONS IN THE OCEAN

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ABSTRACT

As a part of the JGOFS synthesis and modeling project researchers have been working to synthesize the WOCE/JGOFS/NOAA global carbon survey data to better understand carbon cycling in the oceans. Working with international investigators we have compiled a Pacific Ocean data set with over 35,000 unique sample locations analyzed for at least two carbon parameters. These data are being used to estimate the distribution of anthropogenic CO_2 in the oceans. Parallel U.S. WOCE programs, conducted on the same cruises, have investigated the distributions of other anthropogenic tracers (*e.g.* chlorofluorocarbons and radiocarbon). This study examines the distribution of anthropogenic CO_2 recently estimated for the Pacific Ocean (Sabine et al., 2001). The observed trends will be compared and contrasted with observed CFC and bomb ^{14}C distributions in the Pacific. These three anthropogenic tracers have many similarities that are generally related to the large-scale circulation features in the Pacific. There are also several significant differences. Many of these differences can be attributed to the different atmospheric histories and equilibration times. The data-based distributions are also compared with results from the large number of global ocean carbon models that participated in the Ocean Carbon-cycle Model Intercomparison Project (OCMIP).

1. INTRODUCTION

Data-based estimates of the current oceanic anthropogenic CO_2 inventories and transports have been greatly improved over the past decade by the global survey efforts of the World Ocean Circulation Experiment (WOCE), the Joint Global Ocean Flux Study (JGOFS), and the National Oceanographic and Atmospheric Administration's (NOAA) Ocean Atmosphere Carbon Exchange Study (OACES). By working together, these programs have produced a large number of high quality measurements of important anthropogenic tracers such as dissolved inorganic carbon (DIC), chlorofluorocarbons (CFCs), ^{13}C and ^{14}C, as well as other chemical species important in the study of biogeochemical cycling. Data from these cruises are now becoming available and synthesis results are being published. The Pacific Ocean is an important component in the global assessment of the oceanic uptake of anthropogenic CO_2. It accounts for nearly half of the total ocean volume and variability in the CO_2 fluxes from the equatorial Pacific associated with El Niño events may be responsible for up to one third of the interannual variability in atmospheric CO_2 growth rate. The multidisciplinary nature of the global survey program has provided an opportunity to directly compare the distributions and inventories of several different anthropogenic tracers collected at the same locations at the same time. By examining the similarities and differences between these different tracers one can begin to assess the dominant mechanisms controlling their distributions. This work takes a first look at the recent estimates of anthropogenic CO_2 in the Pacific and compares these distributions with other anthropogenic tracers in the Pacific.

2. THE WOCE/JGOFS/OACES DATA

Between 1991 and 1996, carbon measurements were made on twenty-four cruises in the Pacific Ocean. This research was a collaborative effort between 15 laboratories and 4 countries. At least two carbon parameters were measured on almost all cruises, but the choice of which carbon pairs were measured varied

between cruises. The quality of the carbon data was evaluated by Lamb et al. (2001). A set of adjustments for certain cruises were recommended based on many lines of evidence including comparison of calibration techniques, results from certified reference material analyses, precision of at-sea replicate analyses, agreement between shipboard analyses and replicate shore-based analyses, comparison of deep water values at locations where two or more cruises overlapped or crossed, consistency with other hydrographic parameters, and internal consistency with multiple carbon parameter measurements. They estimated that the overall accuracy of the dissolved inorganic carbon (DIC) data was ~ 3 μmol kg^{-1}. Total alkalinity, the second most common carbon parameter analyzed, had an overall accuracy of ~ 5 μmol kg^{-1}. The TA was calculated for all cruises where TA was not measured using DIC and pCO_2 or DIC and pH measurements together with the carbonate dissociation constants of Merbach (1973) as refit by Dickson and Millero (1987) and ancillary constants listed in the program of Lewis and Wallace (1998). The final data set contained about 35,000 sample locations with DIC and TA values.

The corresponding chlorofluorocarbon (CFC) data were compiled and evaluated by the US WOCE CFC consortium. The Pacific synthesis of the chlorofluorocarbon data, lead by J. Bullister, examined the overall quality of the data and ensured that all of the values were reported on the same concentration scale. Although no adjustments were made to the final reported CFC values, the data were carefully flagged based on examination of the entire data set.

In total, nearly 10,000 samples were collected for $\Delta^{14}C$ analysis as part of the WOCE Pacific radiocarbon program led by R. Key. Large volume samples from the deep Pacific were analyzed using the traditional beta-counting technique at the University of Miami and the University of Washington (G. Östlund and M. Stuiver, respectively). The upper thermocline and surface samples were analyzed by accelerator mass spectrometry (AMS) at Woods Hole Oceanographic Institution (National Ocean Sciences AMS Facility - NOSAMS). When the WOCE sampling began in early 1991 the analytical precision of the AMS technique (~10‰) was not as good as traditional beta-counting of large volume samples (2-4‰). Therefore, for many of the Pacific cruises large volume samples were collected in deep waters where both vertical and horizontal gradients were low. The AMS precision increased rapidly during WOCE from >10‰ to ~4.5‰ with no systematic offsets from the large volume techniques.

3. ANTHROPOGENIC ESTIMATES

Gruber et al. (1996) developed the ΔC* approach for estimating anthropogenic CO_2 in the water column since preindustrial times using measurements of inorganic carbon. Since that time, the approach has undergone slight modifications to improve estimates in other regions including the south Atlantic (Gruber, 1998) and the Indian Ocean (Sabine et al., 1999). The analysis presented here builds upon these previous works, with a few modifications for application in the Pacific Ocean (Sabine et al., 2001). The basic approach is the same as that presented by Gruber et al. (1996), and can be summarized with the following simple equation:

$$C_{anth}\ (\mu mol\ kg^{-1}) = C_m - \Delta C_{bio} - C_{280} - \Delta C_{diseq} \quad (1)$$

Where:

C_{anth} = Anthropogenic carbon concentration
C_m = Measured DIC concentration
ΔC_{bio} = Change in DIC as a result of biological activity (both organic and inorganic)
C_{280} = DIC of waters in equilibrium with an atmospheric CO_2 concentration of 280 μatm
ΔC_{diseq} = Air-sea difference in CO_2 concentration expressed in μmol kg^{-1} of DIC

Bomb derived ^{14}C distributions were estimated in the Pacific using the potential alkalinity technique of Rubin and Key (2001). This approach is similar to the traditional silicate technique for estimating bomb ^{14}C, but builds upon the strong linear relationship observed between potential alkalinity (PALK) and natural ^{14}C in the deep waters, well away from the bomb signal:

$$PALK = (alkalinity + nitrate)*35/salinity \quad (2)$$

$$^{14}C_{natural} = 59-0.962*(PALK-2320) \quad (3)$$

Bomb ^{14}C is estimated from the difference between the measured $\Delta^{14}C$ and the $^{14}C_{natural}$ estimated using these equations.

Since chlorofluorocarbons are anthropogenic compounds, no correction is necessary for a natural signal. However, CFC concentrations in the water column are not only dependant on the atmospheric history, but are also strongly dependant on the water temperature at the time of equilibration. Because the anthropogenic carbon and radiocarbon tracers are not as strongly influenced by temperature their distributions are most similar to the CFC partial pressure, which is the CFC concentration corrected for the solubility (Doney and Bullister, 1992).

4. RESULTS

This work shows that to a first order approximation these three different anthropogenic tracers have similar distributions in the Pacific Ocean (e.g., Figure 1). These similarities demonstrate the importance of large-scale circulation features on the distribution of anthropogenic tracers. The highest inventories of all three tracers are observed in the midlatitudes, with the lowest inventories in the high latitude Southern Ocean and near the Equator. The high inventory regions are associated with convergence zones, where waters with relatively high anthropogenic concentrations are moving into the ocean's interior. The low inventory waters are associated with general regions of upwelling, where relatively old waters with low anthropogenic concentrations are brought near the surface. Some differences can be seen in the location of the local maximums and minimums for the different tracers. Differences in the distribution of these tracers can be related to differences in the equilibration times (weeks for CFC, ~1 year for CO_2, and ~10 years for radiocarbon), differences in the solubilities, and

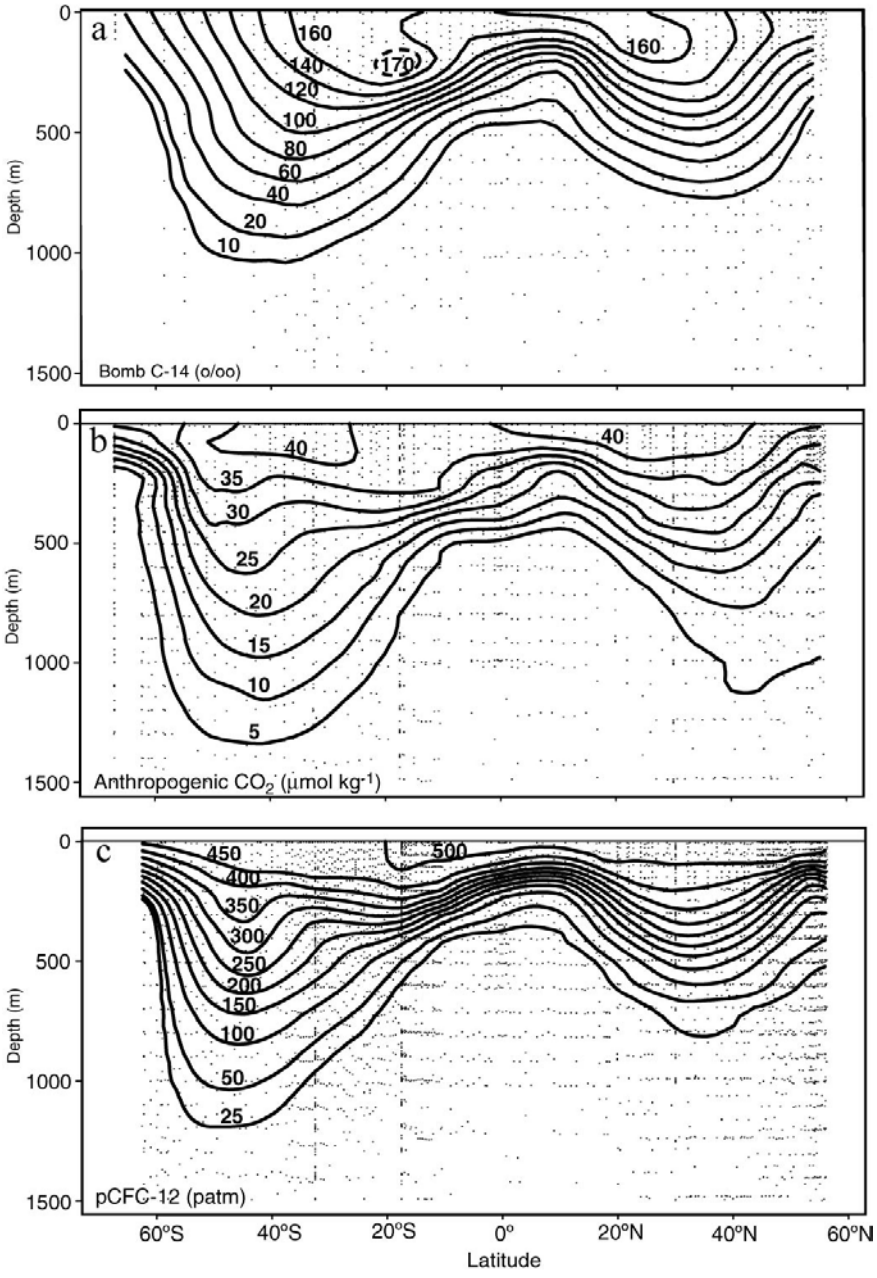

Fig. 1. Meridional sections of bomb ^{14}C (a), anthropogenic CO_2 (b), and pCFC-12 (c) along 150ºW in the central Pacific. Points indicate sample locations. Bomb ^{14}C calculated using data from R. Key (Princeton) using the potential alkalinity method of Rubin and Key (2001). pCFC-12 calculated using data from J. Bullister (PMEL).

differences in the atmospheric histories. For example, the bomb ^{14}C section in Figure 1 shows a subsurface maximum in concentration that is not observed in the other tracers because it is the only tracer that has seen a dramatic decrease in atmospheric concentrations with time.

5. CONCLUSIONS

Studies of the relationships between these different tracers are just beginning. The similarity of the independently derived distributions provides support for the approaches used to estimate the various anthropogenic components. The differences in the distributions are starting to provide useful information on shallow thermocline ventilation processes. For example, all of the anthropogenic tracers show very shallow penetrations in the high latitude Southern Ocean. This is in contrast to some ocean GCMs that suggest much higher anthropogenic inventories in this region. The differences are greatest with models that have large overturning convection in the Southern Ocean.

We are working closely with the modeling community to evaluate global carbon models. The use of multiple tracers is proving to be a powerful tool for the validation of these models. The modeling community, in turn, is helping the observationalists relate observed differences in distributions to oceanographic mechanisms. By using multi-tracer relationships, we hope to better understand the processes involved in the uptake of anthropogenic tracers as well as watermass formation, thermocline ventilation, and mixing rates.

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